

Energy Flow in the Biosphere

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The source of almost all of the energy on Earth is the Sun. Much of the energy that reaches Earth's atmosphere is filtered out before it reaches the surface (**Figure 1**). Only a tiny portion is actually used by green plants for photosynthesis (**Figure 2**). However, as this chapter will discuss, almost all organisms on Earth depend on this energy.

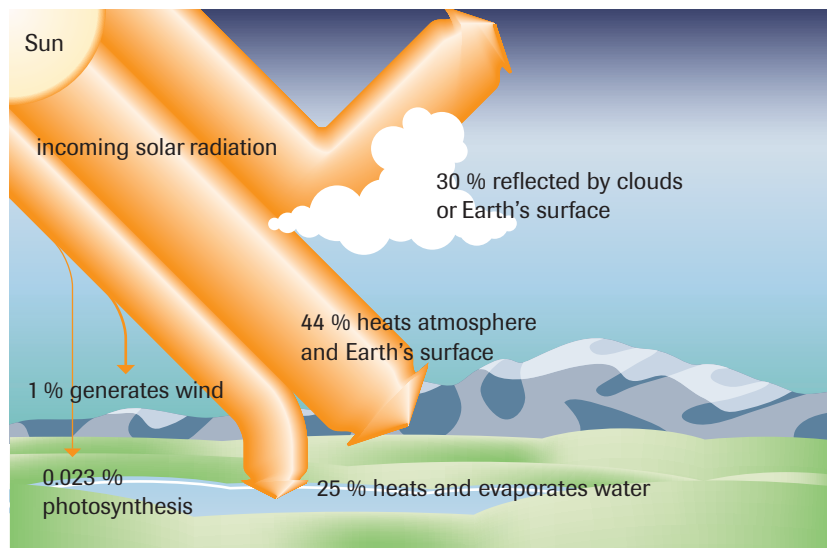



Figure 1

A model of the flow of energy from the Sun, to Earth, and back into space



STARTING Points

Answer these questions as best you can with your current knowledge. Then, using the concepts and skills you have learned, you will revise your answers at the end of the chapter.

1. Predict how increased cloud cover or pollution haze would affect a forest ecosystem.
2. The text above states that the Sun is “the source of almost all of the energy on Earth.” What other source(s) can you think of? How important is each energy source?
3. Is it possible for food chains to exist in a cave or the ocean depths where no sunlight can penetrate? Explain why or why not. 



Career Connection:
Geographer



Figure 2

Photosynthesis is the process by which green plants use solar energy to produce carbohydrates (sugars), which can then be used as food by other organisms. Plants compete for solar energy. In this mixed forest, the various plant species have adaptations that allow them to avoid or tolerate the shade of the plants around them.

► Exploration

Competition between Plants

Changes in the biotic or abiotic factors within an ecosystem often cause one plant community to replace another. In turn, changes in the plant community are accompanied by changes in the animal community. In this activity, you will determine which plant species has an advantage under certain conditions. Each research group can study a different set of variables.

Materials: apron, milk cartons, 9 kinds of vegetable or flower seeds, potting soil, water



Always wash your hands after handling soil.

- As a class, decide on the types of seeds you will plant in each milk carton.
- Fill milk carton with moist potting soil. Divide the soil surface into nine squares.
- In each square, plant two seeds of one of the species according to the instructions on the packets. Water each carton with the same amount of water every second day. Record the amount of water used.
- Once seeds start to germinate, store each carton in a different environment. You could use amount of sunlight, temperature, or amount of water as variables.

- Measure the growth of each plant daily. Record any other observations.
- (a) Does one type of plant begin to dominate the community? Is it the same type of plant in all cartons?
- (b) Choose the most successful plant you grew. Do research to answer these questions: In what environment is this plant naturally found? What does this environment have in common with the conditions you set in the exploration?
- (c) Speculate about why one plant might be better adapted for a specific environment than another.



2.1 Energy Transfer and Food Webs

trophic level a category of living things defined by how it gains its energy; the first trophic level contains autotrophs, and each higher level contains heterotrophs

autotroph an organism that uses the Sun's energy and raw materials to make its own food; a producer

primary consumer in a food chain or food web, an organism that relies directly on autotrophs for its source of energy; organisms at the second trophic level

secondary consumer in a food chain or food web, an organism that relies on primary consumers for its principal source of energy; organisms at the third trophic level

heterotroph an organism that is incapable of making its own food, and so must feed on other organisms to gain energy

You can begin to understand how energy flows through ecosystems by categorizing living things by their **trophic level**, according to how they gain their energy. The term *trophic* comes from a Greek word meaning “feeder.”

Organisms that can make their own food from basic nutrients and sunlight or some other non-living energy source are placed in the first trophic level (**Figure 1**). Not surprisingly, these organisms are also referred to as producers or **autotrophs** (from Greek words meaning “self-feeders”). Plants, algae, and some types of bacteria are in the first trophic level.

The second trophic level contains organisms that feed on the producers. These organisms are referred to as **primary consumers**. Primary consumers rely on autotrophs directly for their source of energy.

Secondary consumers are animals in the third trophic level. They rely on primary consumers for their source of energy, but they are still dependent on the autotrophs in the first trophic level. Although a wolf eats other animals, it still relies indirectly on the photosynthesis of plants for energy. The deer that the wolf eats has eaten grass or the buds of a spruce tree.

Consumers, at whatever trophic level, are sometimes called **heterotrophs**. Heterotrophs cannot make their own food, and so must obtain their food and energy from autotrophs or other heterotrophs. Human beings are heterotrophs.

DID YOU KNOW?

An Alternative View

One Aboriginal approach to trophic levels is to rank them according to dependence. Primary consumers depend on autotrophs, and secondary consumers depend on the primary ones. Humans are the most dependent consumers.

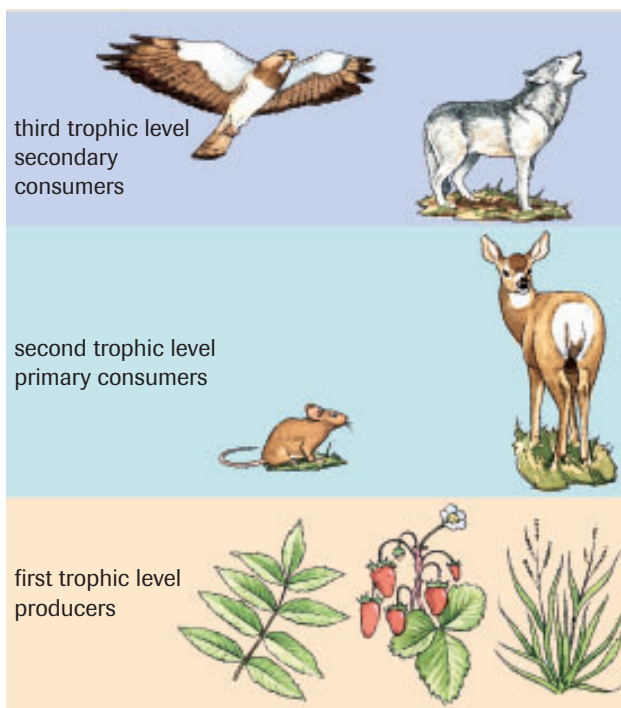


Figure 1

Trophic levels, showing producers and consumers. An ecosystem may contain more than three trophic levels.

Energy and Food Chains

Every organism within an ecosystem provides energy for other organisms. Food chains are a way of showing a step-by-step sequence of who eats whom in an ecosystem. The sequence in **Figure 2** shows a one-way flow of energy in a simple food chain from producer to secondary consumer. The deer does not make its own energy; instead, it relies on the spruce tree. The deer is a heterotroph. Since the deer receives its energy two steps away from the original source (sunlight), it is in the second trophic level. Using the same reasoning, the wolf, also a heterotroph, is a member of the third trophic level.

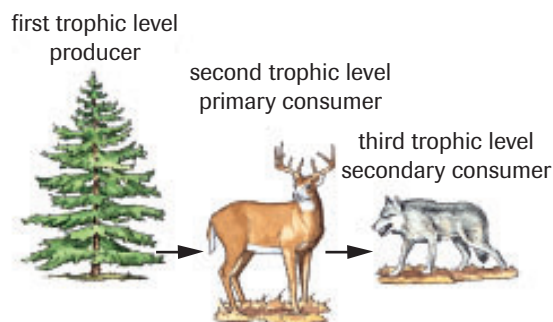


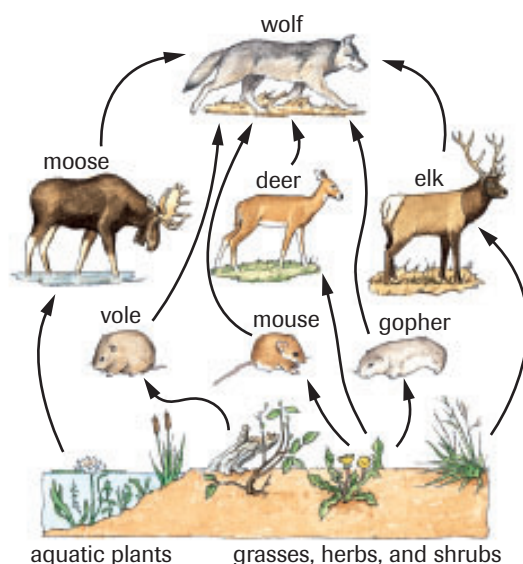
Figure 2

In this food chain, energy flows from a producer (the spruce tree), to a primary consumer (the deer), to a secondary consumer (the wolf).

Consumers are placed in categories based on their trophic level in a food chain. A carnivore directly feeding on a primary consumer is a secondary consumer. However, if the carnivore eats a secondary consumer (another carnivore), it is now a tertiary consumer—it is at the fourth trophic level. The final carnivore in any food chain is called a top carnivore. Top carnivores are not eaten by other animals (at least, while they are alive). In the example above, the wolf is both a secondary consumer and a top carnivore, since it obtains its energy from the deer and no other animal eats the wolf.

Food Webs

The food chain shown in **Figure 2** would be highly unlikely to include all the organisms in a natural ecosystem. In reality, deer also eat buds, stems, bark, and grasses. The wolf includes in its diet many different animals, such as rabbits, ground-nesting birds and their eggs, beavers, and muskrats. Each individual organism in an ecosystem is involved in many food chains. The chains all interlock with each other to form a feeding relationship called a **food web** (**Figure 3**).



+ EXTENSION



Decomposers

Decomposers do not always fit neatly into one position in food webs or trophic levels. Listen to this Audio Clip to learn more about the role of decomposers in ecosystems.

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food web a representation of the feeding relationships among organisms in an ecosystem

Figure 3

A simplified food web shows the wolf as the top carnivore and plants as producers. Notice that both the vole and the deer belong in the second trophic level of this web. Of course, in a real ecosystem, the food web would be much more complicated. It would include most of the organisms in the ecosystem.



CHEMISTRY CONNECTION

Chemical Bonds

Your Chemistry textbook has more information on the nature of chemical bonds, and energy changes during bond-making and bond-breaking.

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photosynthesis the process by which green plants and some other organisms use solar energy, carbon dioxide, and water to produce carbohydrates

cellular respiration the process by which cells break down glucose into carbon dioxide and water, releasing energy

chemosynthesis the process by which non-photosynthetic organisms convert inorganic chemicals to organic compounds without solar energy

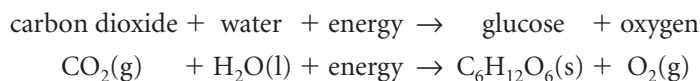
chemoautotroph an organism that can synthesize organic compounds from inorganic chemicals without using solar energy

The most stable ecosystems, those with the greatest biodiversity, have such complex and well-developed food webs that the reduction in numbers or even the complete removal of one type of organism may have only a small effect on the overall web. Predict what would happen to the organisms in **Figure 2**, on the previous page, if deer depended exclusively on the buds of spruce trees for food, and spruce budworm were introduced. Spruce budworms also eat the buds of spruce trees. What would happen to the deer and the wolves if spruce budworms ate most of the spruce buds? If this food chain showed all the organisms in the ecosystem, you would predict that the deer and wolves would be deprived of food and would die. In fact, if spruce budworms eat most of the spruce buds, deer may switch to another tree or grass, and wolves may not be much affected.

However, where abiotic factors limit the number of organisms, the webs begin to look more like food chains. This is particularly true in the Arctic, where the number of producers is small. Because there is less energy available from the Sun and temperatures are often low, producers in the Arctic cannot photosynthesize as rapidly as they do in the south. Less energy is available, so fewer organisms can live in that ecosystem. The limited number of organisms means that their relationships with each other are more direct. In these situations, the loss of any one member will have a profound effect on all the remaining organisms. The lower the biodiversity of an ecosystem, the simpler the food web, and the more vulnerable each organism is to changes in the ecosystem.

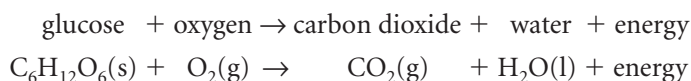
Photosynthesis and Respiration

Food webs always begin with autotrophs, such as plants. All living things use some form of chemical energy for food. Green plants make their own food by using carbon dioxide (CO_2) and water (H_2O), plus energy from sunlight, to make molecules of a sugar, glucose ($\text{C}_6\text{H}_{12}\text{O}_6$). This process, called **photosynthesis**, captures solar energy and stores it in the chemical bonds of glucose. You can read more about photosynthesis in Chapter 6. The reaction below summarizes photosynthesis.



Since photosynthetic organisms are at the first trophic level, photosynthesis ultimately provides the energy required by the entire ecosystem. Photosynthesis absorbs energy from an abiotic component of an ecosystem (sunlight) and moves it into biotic components (green plants). As one moves up through the trophic levels of an ecosystem, this energy is then transferred to different organisms through the food they eat.

All organisms, including plants, undergo **cellular respiration** in order to use the energy in their food. Cellular respiration breaks down glucose, releasing the energy stored in its bonds. Some of this energy is used to fuel cell processes, and some is released in the form of thermal energy. You can read more about cellular respiration in Chapter 7. The reaction below summarizes cellular respiration.



If you look at the two reaction equations, you will see that they are the reverse of one another. The processes of photosynthesis and cellular respiration are therefore said to be complementary. Since these two processes are complementary, a balance of oxygen and carbon dioxide is maintained within any ecosystem. The plants produce oxygen and glucose during photosynthesis, while all organisms produce carbon dioxide and water

during cellular respiration (Figure 4). Since plants carry out both photosynthesis and respiration, you might think that plants could maintain the balance between oxygen and carbon dioxide themselves. However, plants produce about nine times the amount of oxygen by photosynthesis that they use up in cellular respiration.

Chemosynthesis

Not all food webs begin with photosynthetic organisms. In a few ecosystems, such as in caves or the deep oceans, producers convert simple molecules into more complex compounds without solar energy, by a process called **chemosynthesis**. These bacteria are **chemoautotrophs**, which are organisms that require only carbon dioxide, water, and an energy source (other than solar energy) to make nutrients. Chemical energy is extracted from inorganic chemicals such as hydrogen sulfide (H_2S), ammonia (NH_3), ferrous ions (Fe^{2+}), or sulfur (S_8).

In sulfur hot springs, such as those in Banff National Park, thermal energy generated within Earth's crust heats underground water, which is then released through vents in the rock. Some bacteria use the thermal energy to convert dissolved hydrogen sulfide and carbon dioxide into organic compounds. These bacteria, as producers, become a food source for tiny consumers in this ecosystem. Figure 5 shows a food chain that depends on chemosynthesis.

Limits on Energy Transfer

Every time energy is transferred between the components of an ecosystem, the amount of energy available to the next trophic level is reduced. Why? One reason is that whenever energy is transferred, some of the energy is transformed to a different form. Some energy is released as thermal energy during cellular respiration. Some of it is converted to other chemical energy in molecules other than glucose. The organisms at the next trophic level may not be able to use all these molecules as a source of energy. Let's return to the simple spruce → deer → wolf food chain.

- Through photosynthesis, producers such as the spruce tree use solar energy to make molecules of glucose. The plant then uses most of that energy to carry out the processes it needs to live and to manufacture the chemicals it needs to grow. Therefore, not all of the chemical energy captured during photosynthesis is available to an animal that eats the spruce tree.
- Primary consumers, such as the deer, rely on the chemical energy produced by plants to sustain their lives. A deer does not digest all of a meal of spruce buds. Some is eliminated in the deer's feces (wastes). Some of the remaining energy is lost as thermal energy during the chemical transformations of digestion. Some of the remainder is used to fuel the deer's cells through cellular respiration, which also releases thermal energy. Some of that thermal energy is used to maintain the deer's body temperature, but eventually all of the thermal energy released is lost to the surrounding air. Only about 10 % of the energy in the spruce buds is transferred to the deer. It uses this energy to move its limbs, pump its blood, and manufacture the molecules it needs to carry out its life processes and grow.
- Like the deer, the wolf loses some of the energy in its meal during digestion and body maintenance. Therefore, only about 10 % of the energy in the wolf's meal is transferred to the wolf.

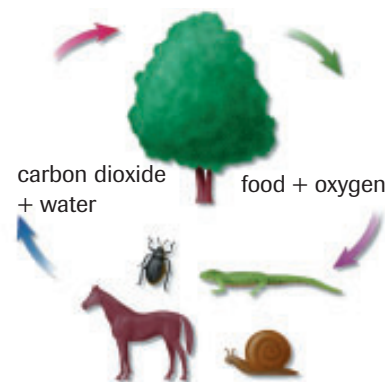


Figure 4

The byproducts that plants release in photosynthesis support animals. The waste products that both animals and plants produce in cellular respiration support plants.

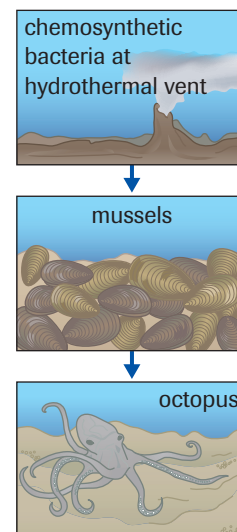


Figure 5

In this food chain, bacteria use the thermal energy from hydrothermal vents on the ocean floor to make nutrients.

+ EXTENSION

Chemosynthetic Food Chains

Listen to a discussion of energy sources that may be used by chemoautotrophs.

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In all food chains, whether the producers are photosynthetic organisms or chemoautotrophs, the farther up the chain you travel, the less energy is available (**Figure 6**). In every ecosystem, less energy is available to secondary consumers than to primary consumers. In general, the overall loss of energy at each step limits the number of trophic levels in a food chain to about five. This is supported by the laws of thermodynamics.

Laws of Thermodynamics

Thermodynamics is the study of energy transformations. The energy flowing from the Sun through ecosystems illustrates the laws of thermodynamics.

- The *first law of thermodynamics* states that although energy can be transformed (changed) from one form to another, it cannot be created or destroyed.
- The *second law of thermodynamics* states that during any energy transformation, some of the energy is converted into an unusable form, mostly thermal energy, which cannot be passed on. Each time energy is transformed, some energy is lost from the system. As a result, the amount of energy available in each step of a chain of transformations is always less than the amount of energy available at the previous step. This applies to all systems, including food chains (**Figure 7**).

thermodynamics a scientific study of energy transformations, described by laws

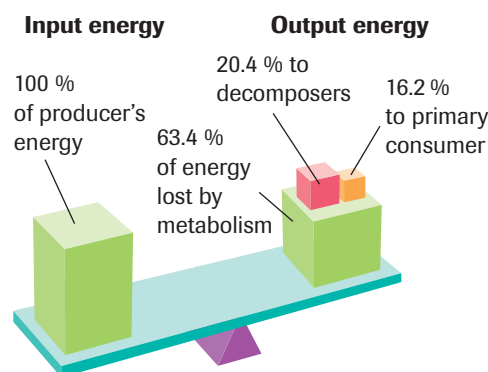


Figure 6
Most of the energy transformed from solar energy to chemical energy by a plant is used to maintain the plant and to grow. Every time the plant uses some of its energy store, it also loses energy as thermal energy. As a result, when the plant is eaten, only a small amount of energy is available for the primary consumer and decomposers.

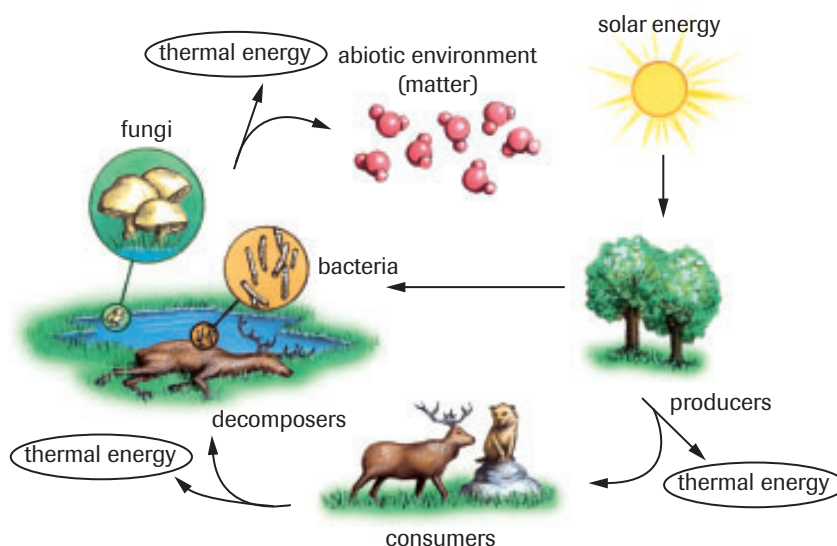


Figure 7
According to the second law of thermodynamics, energy is lost each time energy is transferred from one organism to another, and inside each organism as it uses the energy to survive.

INVESTIGATION 2.1 Introduction

Constructing Food Webs

In Part 1 of this Investigation, you will research an Antarctic ecosystem and connect the organisms in a food web. In Part 2, you will construct a food web of organisms found in your community.

Report Checklist

- | | | |
|----------------------------------|--|---|
| <input type="radio"/> Purpose | <input checked="" type="radio"/> Design | <input checked="" type="radio"/> Analysis |
| <input type="radio"/> Problem | <input type="radio"/> Materials | <input type="radio"/> Evaluation |
| <input type="radio"/> Hypothesis | <input checked="" type="radio"/> Procedure | <input type="radio"/> Synthesis |
| <input type="radio"/> Prediction | <input checked="" type="radio"/> Evidence | |

To perform this investigation, turn to page 35.



Web Quest—Designing Food Webs

There are many different food webs in our world, some containing familiar organisms, others filled with exotic species. Drawing food webs by hand and analysing them can be difficult. In this Web Quest, you will use the computer to build a food web. You can then easily study the interactions by adding and removing organisms and seeing the result.

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SUMMARY

Energy Transfer and Food Webs

- Food chains describe relationships between lower and higher trophic levels and describe the flow of energy within an ecosystem.
- Energy is transferred to organisms at the next trophic level in a food chain or food web. At each transfer, some energy is transformed into thermal energy and is no longer available.
- During photosynthesis, plants use solar energy to combine carbon dioxide and water. Photosynthesis can be summarized by the equation:

$$\text{carbon dioxide} + \text{water} + \text{energy} \rightarrow \text{glucose} + \text{oxygen}$$
- The energy required for almost all living organisms originates with solar radiation, which is converted to chemical energy during photosynthesis and stored in the chemical bonds of sugars such as glucose. In the cells, cellular respiration breaks down the chemical bonds, releasing the energy to be used for growth and metabolism. Cellular respiration can be summarized by the equation:

$$\text{glucose} + \text{oxygen} \rightarrow \text{water} + \text{carbon dioxide} + \text{energy}$$
- Chemoautotrophic organisms produce chemical energy without solar energy, and provide the base of food pyramids in those rare ecosystems with little or no sunlight.

Section 2.1 Questions

1. In your own words, explain what is meant by the term *trophic level*.
2. What type of food would be consumed by a secondary consumer? Explain your answer.
3. Distinguish between a food chain and a food web. Give examples of each.
4. Identify the reactants and products for the chemical reaction of photosynthesis.
5. Identify the reactants and products for the chemical reaction of cellular respiration.
6. What source of energy is used by chemosynthetic bacteria to make organic compounds?
7. In your own words, explain the first and second laws of thermodynamics.
8. Explain why only about 10 % of the energy available in a plant is transferred to the primary consumer.

2.2 Scientific Models

DID YOU KNOW?

Speed and the Dinosaur

From fossil evidence, some scientists suggested that *Tyrannosaurus rex* was capable of speeds in excess of 70 km/h. However, by using mathematical models, other scientists have calculated that *T. rex* would be killed if it ever tripped. The tiny forelimbs were much too small to offer protection to such a heavy animal at such speeds. They calculated that *T. rex* would skid for more than 40 metres after tripping if it ran at such speeds. Falling would create a force on the chest equivalent to a 36 tonne mass (352 800 N), easily crushing the dinosaur's ribs. Even greater damage would occur to the head. A fall would apply a force equivalent to a 13.6 tonne mass (133 820 N), enough to snap its neck. These new calculations have caused scientists to estimate that *T. rex* likely didn't run any faster than 15 km/h.

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ecological pyramid a representation of energy flow in food chains and webs

Scientists often construct models to help them understand how living things function. Models are theoretical descriptions or analogies that help us visualize something that has not been directly observed. For example, a scientist might reconstruct the climatic conditions of 65 million years ago to uncover what might have happened to the dinosaurs. Indirect fossil evidence is used to gather information on weather patterns and vegetation cover in an ecosystem. Plants such as ferns are unable to live in hot, arid conditions or in extreme cold. When fossils of ferns are found, scientists are able to make inferences about climate range.

The advantage of scientific models is that they provide a pathway for making predictions. Scientists often use mathematical models, which exist only as equations, to help them understand biological observations. There are three essential steps in formulating a mathematical model:

1. making an estimate and developing an equation based upon indirect data and background information;
2. computing the prediction implied by the equation; and
3. comparing the prediction with future or past events. Supporting evidence is gathered to make sure that the mathematical model does not support just one situation. If this is ever shown to be the case, then the model is rejected.

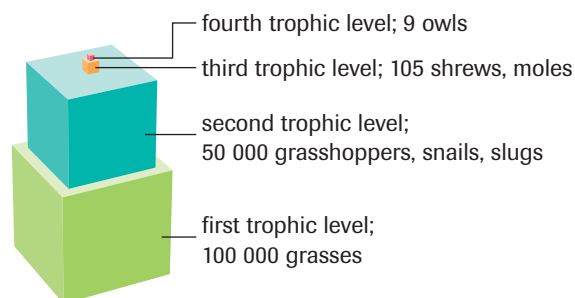
A good mathematical model can be used to test and predict the implications of many different courses of action. By being tested on past events, the model gains acceptance in predicting future events.

Ecological Pyramids

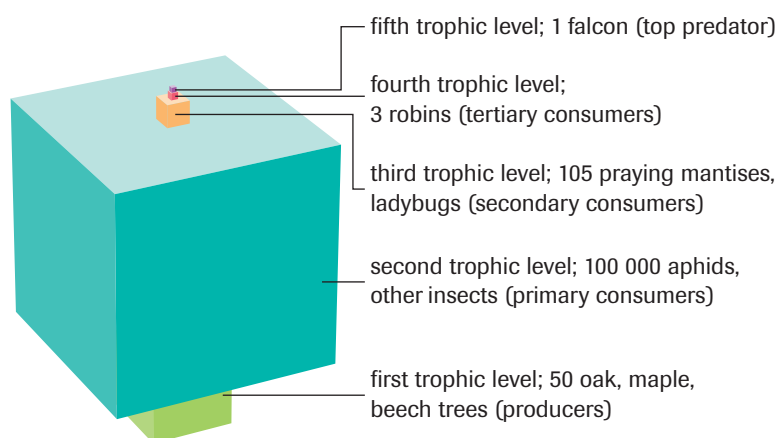
Graphs called **ecological pyramids** can be used to represent energy flow in food chains and food webs or the populations of organisms in a food chain. These graphs help the ecologist visualize more clearly the relationships in an ecosystem and compare ecosystems.

Pyramids of Numbers

A pyramid of numbers can be drawn by counting the number of organisms at each trophic level in an ecosystem. When these numbers are then represented on a vertical graph, with the volume of each level representing the number of organisms at that level, the graph sometimes takes on the general shape of a pyramid (**Figure 1**, next page). However, ecologists have found that, in some cases, the shape is not like a pyramid because of the physical size of the members of a food chain. For example, many tiny aphids (an insect that feeds by sucking sap from plants) may be found feeding off a single plant (**Figure 2**, next page).

**Figure 1**

A pyramid of numbers for a grassland ecosystem. In this ecosystem, the number of producers is greater than the number of primary consumers.

**Figure 2**

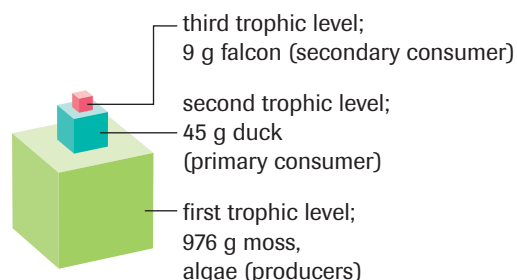
A pyramid of numbers for a deciduous forest ecosystem. Because an aphid is much smaller than a tree, a single plant may provide food for thousands of aphids.

Pyramids of Biomass

Biomass is the total dry mass of all the living material in an ecosystem. Since organisms store energy as organic molecules, biomass is a measure of stored energy content. To understand this idea, compare a rainforest ecosystem with a tundra ecosystem. Rainforest ecosystems are located in tropical areas with intense sunlight. A rainforest ecosystem would be able to store large amounts of energy from the Sun. As a result, it would contain a large amount of organic material and have a large total biomass. In contrast, tundra ecosystems are located in northern areas with less intense sunlight and long, dark winters. A tundra ecosystem would be able to store less energy, and thus would contain a smaller amount of organic material and have a lower total biomass.

A pyramid of biomass is a useful way to represent an ecosystem. To make such a pyramid, the dry mass (after water has been removed) of the tissue in the plants or animals is measured and graphed (**Figure 3**). Occasionally, a graph of biomass is not a regular pyramid. Such ecosystems, however, are rare.

biomass the total dry mass of all the living material in an ecosystem

**Figure 3**

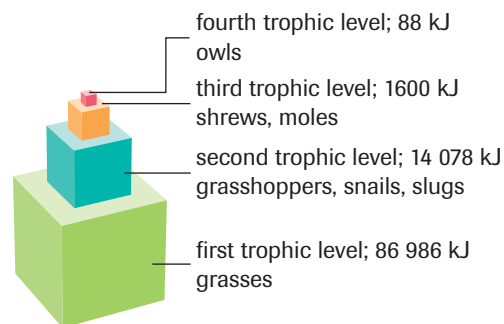
A pyramid of biomass for a Newfoundland peat bog. The numbers represent the dry mass (g) for all organisms at that trophic level found in 1 m². As you can see, there is less biomass at each trophic level.

Pyramids of Energy

It is possible to measure the amount of energy available at each trophic level. Creating a pyramid graph allows us to better understand the relationships and energy flow (**Figure 4**, next page). The comparatively larger mass of the individual tertiary consumers and the vast amount of energy that they expend while hunting limits the number of individuals that can be supported at the top position of the pyramid.

Figure 4 

A pyramid of energy for a grassland ecosystem. At each level, the energy found in the bodies of the organisms is graphed. The larger the volume of the level, the greater the energy at that level. As you can see, only about one-thousandth of the chemical energy from photosynthesis stored in the producers in this food web actually reaches the top predator (the owl) at the fourth trophic level. Energy is measured using joules (1000 joules (J) = 1 kilojoule (kJ)).



As you learned in the previous section, most of the energy at each level of a food chain is used and/or lost as heat. Only a fraction of the energy passes from one level of a food chain to the next. This fraction is often said to be about $\frac{1}{10}$, or 10 %. Although this number is just an approximation, it can be useful for making estimations. For example, if the grasses in an ecosystem produce 1×10^{10} kJ of energy per year, you can estimate that the primary consumers in that ecosystem can only obtain 1×10^9 kJ per year by eating the grasses. Secondary consumers will only obtain about 1×10^8 kJ per year. (Note that these estimations are extremely simplified. Calculations are more often done for energy per gram, or per square metre, rather than for an entire ecosystem.)

Look at the sample exercise below to learn how to create two- and three-dimensional pyramids. The second sample exercise shows how to calculate energy loss through a food chain.

SAMPLE exercise 1

Pyramids of energy are graphical representations that show energy flow in food chains and webs. As energy is lost, fewer organisms can be supported at each successive level. The base of the pyramid always indicates the total amount of energy held by producers. Use the data in **Table 1** to construct a two-dimensional energy pyramid.

Table 1 Energy Pyramid Data

Trophic level	Energy (kJ)	Area of the box (mm ²)
producers (first trophic level)	100 000	1 000
consumer (second trophic level)	15 000	
consumer (third trophic level)	1 000	

Solution

1. Establish a ratio between the area of the box and the amount of energy held by the producers. For two-dimensional pyramids, the amount of energy held by producers is displayed as a ratio of the area of the box at the base of the pyramid.

$$\begin{aligned}\text{energy} &= \text{area of the box at the base of the pyramid} \\ 100\,000 \text{ kJ} &= 1000 \text{ mm}^2\end{aligned}$$

2. Determine length and width of the producer box.

$$\begin{aligned}1000 \text{ mm}^2 &= \text{width} \times \text{length} \\ 1000 \text{ mm}^2 &= 20 \text{ mm} \times 50 \text{ mm}\end{aligned}$$

Draw the box with these dimensions (**Figure 5 (a)**, next page).

3. Use the ratio for producers to establish the size of the box for second-level consumers.

$$\frac{\text{area of box for producer}}{\text{energy of producer}} = \frac{\text{area of box for second-level consumer}}{\text{energy of second-level consumer}}$$

$$\frac{1000 \text{ mm}^2}{100\,000 \text{ kJ}} = \frac{x}{15\,000 \text{ kJ}}$$

$$x = \frac{1000 \text{ mm}^2 \times 15\,000 \text{ kJ}}{100\,000 \text{ kJ}}$$

$$x = 150 \text{ mm}^2$$

4. Determine the length and width of the second-level consumer box.

$$150 \text{ mm}^2 = \text{width} \times \text{length}$$

$$150 \text{ mm}^2 = 30 \text{ mm} \times 5 \text{ mm}$$

Draw the box with these dimensions on top of the producer box (**Figure 5 (b)**).

5. Repeat for the third-level consumer box.

$$\frac{\text{area of box for producer}}{\text{energy of producer}} = \frac{\text{area of box for third-level consumer}}{\text{energy of third-level consumer}}$$

$$\frac{1000 \text{ mm}^2}{100\,000 \text{ kJ}} = \frac{x}{1000 \text{ kJ}}$$

$$x = \frac{1000 \text{ mm}^2 \times 1000 \text{ kJ}}{100\,000 \text{ kJ}}$$

$$x = 10 \text{ mm}^2$$

6. Determine the length and width of the third-level consumer box.

$$10 \text{ mm}^2 = \text{width} \times \text{length}$$

$$10 \text{ mm}^2 = 5 \text{ mm} \times 2 \text{ mm}$$

Draw the box (**Figure 5 (c)**).

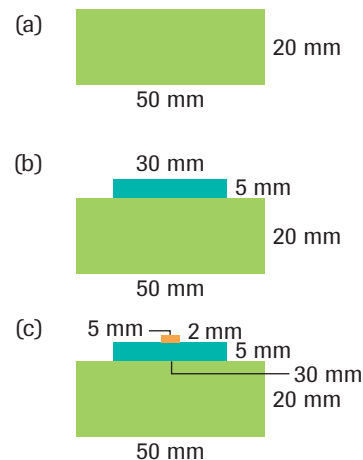


Figure 5

Constructing an energy pyramid

Practice

1. Draw two-dimensional and three-dimensional pyramids using the data in **Table 2**, of an Alberta mixed woodland ecosystem.

Table 2 Pyramid of Numbers

Trophic level	Number of organisms
producers (trees and shrubs) first trophic level	100
consumers (insects, slugs, snails) second trophic level	9800
consumers (ladybugs, praying mantises) third trophic level	500
consumers (shrews, moles, robins) fourth trophic level	10
consumers (hawks, falcons, snakes) fifth trophic level	3

► **SAMPLE** exercise 2

As shown below, phytoplankton are at the base of an ocean food chain.

phytoplankton → zooplankton → herring → salmon

- If the phytoplankton in an ecosystem produce 20 000 000 kJ of energy per day, how much energy is available for the salmon?
- Suppose each herring requires 1000 kJ of energy per day to survive. How many herring can this ecosystem support?

Solution

- Assume that 10 % of the energy passes from each level of the food chain to the next. Calculate the amount of energy that reaches the top level of the food chain.
 $20\,000\,000\text{ kJ} \times 0.10 = 2\,000\,000\text{ kJ}$ (energy that will reach the zooplankton)
 $2\,000\,000\text{ kJ} \times 0.10 = 200\,000\text{ kJ}$ (energy that will reach the herring)
 $200\,000\text{ kJ} \times 0.10 = 20\,000\text{ kJ}$ (energy that will reach the salmon)
 Thus, 20 000 kJ of energy is available for the salmon each day.
- You know that 200 000 kJ of energy is available for the herring each day. Divide this number by the amount of energy required by each herring.
 $200\,000\text{ kJ} \div 1000\text{ kJ/herring} = 200\text{ herring}$
 The ecosystem can support 200 herring.

► **Practice**

- Draw a two-dimensional energy pyramid for the following food chain. Use the data from the sample exercise and solution.
 phytoplankton → zooplankton → herring → salmon
- An ecosystem contains 1000 bushes and grasses. Each produces about 10 000 kJ of energy per day.
 - How many rabbits can be supported by this ecosystem, if each rabbit requires 5 000 kJ of energy per day?
 - How many foxes can be supported by this ecosystem, if each fox requires 10 000 kJ of energy per day?
 - Draw a pyramid of numbers for this ecosystem.



INVESTIGATION 2.2 Introduction

Light Intensity and Plant Biomass

Through photosynthesis, plants capture solar energy and use it to combine water and oxygen into glucose. Glucose is then used to fuel its cellular activities and to build other molecules required by the plant. These molecules are used in plant growth, which increases the mass and size of the plant. How does light intensity affect plant biomass? In this investigation, you will design and carry out your own experiment to address this problem.

Report Checklist

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| <input type="radio"/> Purpose | <input type="radio"/> Design | <input checked="" type="radio"/> Analysis |
| <input checked="" type="radio"/> Problem | <input type="radio"/> Materials | <input checked="" type="radio"/> Evaluation |
| <input type="radio"/> Hypothesis | <input checked="" type="radio"/> Procedure | <input type="radio"/> Synthesis |
| <input checked="" type="radio"/> Prediction | <input checked="" type="radio"/> Evidence | |

To perform this investigation, turn to page 36.

Human Use of Energy in Ecosystems

Like all other living things, humans are dependent on the energy flow through ecosystems. We are part of many food chains at different levels. For example, a person eating vegetables is a primary consumer; a person eating steak is a secondary consumer; and a person eating salmon may be a tertiary consumer, depending on the salmon's diet. Unlike most other living things, humans also use the energy in ecosystems in other ways. For example, we burn wood for fuel, obtaining the energy trapped in it by photosynthesis.

Human use of the energy in an ecosystem often changes the ecosystem itself. Most ecosystems can adapt to small changes, such as the removal of a few salmon. Large-scale changes in ecosystems, however, often permanently change the types and sizes of populations of organisms found in that ecosystem. For example, humans have permanently changed many ecosystems in order to grow and hunt food. Hunting, fishing, and extensive crop growth have impacted many large ecosystems (**Figure 6**).

Hunting and Fishing

The science of wildlife management involves the manipulation of populations of wild species and their habitats for the benefit of humans. In the past, over-hunting of wild species such as wolves and buffalo have led to extirpation and large changes in ecosystems. Today, however, conservation groups like the Sierra Club and the Defenders of Wildlife recognize hunting and fishing as acceptable management tools.

A confrontation between technology and nature is unfolding in Canadian coastal waters. Improved factory ships, larger nets, improved technology for fish detection, and more boats have dramatically increased the harvest of marine fish. As a result, prized fish such as cod, halibut, and salmon have been drastically reduced. The pursuit of short-term economic gain at the expense of long-term economic collapse from overfishing is an important issue that governments must address.

Monocultures

Fossil records tell us that biological diversity has increased over time. About 150 different families of animals existed at the end of the Cambrian period 500 million years ago. Since then the number has increased to nearly 800 (**Figure 7**). This represents over two million species. However, most biologists will argue that this number is very conservative. There may be as many as 15 million different species of organisms now living on Earth.

Historically, humans have used about 700 different species of plants. According to the noted biologist Edward Wilson, today we rely heavily on about 20 species—wheat, rice, cotton, barley, and corn being the most important. Most human agriculture has



Figure 6

Cultivation of the land has disrupted many food chains. In Alberta, European settlers who selected monocultures of wheat and barley in favour of natural grasses contributed to a decline in the populations of mule deer, bison, elk, and moose, while increasing the range and number of whitetail deer.

CAREER CONNECTION



Geographer

Geographers study physical aspects of particular biological or physical regions. They often use satellite and imagery technologies to provide information on environmental issues, study the large-scale effects of human activity, or coordinate development plans with land-use planners. Learn more about geographer specializations and decide if this career direction is right for you.

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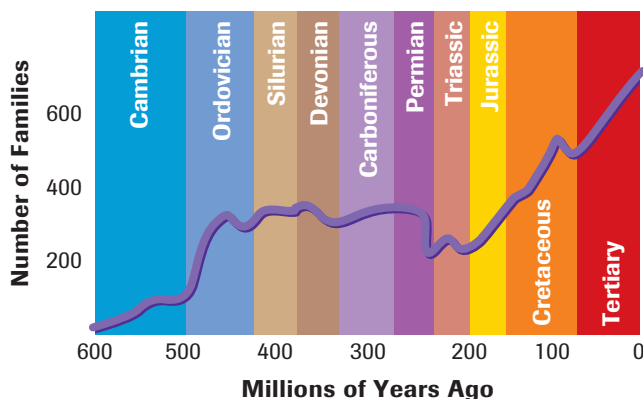


Figure 7

The graph shows a trend toward greater biodiversity.

monoculture cultivation of a single species



Figure 8
Many different species of plants can be found in a rain forest.

been directed at producing food crops. However, many wild plants are also important to humans. For example, the rosy periwinkle, a plant native to Madagascar, produces two important chemicals that are useful in treating Hodgkin's disease, a form of leukemia, or cancer of the white blood cells. Unfortunately, many wild plants have already been destroyed to grow food crops, especially in tropical rain forests.

The nutrient-poor soil of the tropical rain forests is not well suited for **monocultures** of cereal grains such as wheat and barley. These soils require the renewal of decomposed matter to maintain adequate levels of nitrogen and phosphorus. Nitrogen and phosphorus cycles should not be disrupted in the delicate rain forests (**Figure 8**). A few seasons after planting, the soil will no longer support the growth of crops. What makes the situation even more critical is that the greatest biodiversity exists in the tropical rain forests. Many species have yet to be classified, let alone investigated for possible medicines.

SUMMARY *Scientific Models*

- Mathematical models are theoretical models that exist as equations. These models are used to make non-intuitive and testable predictions that follow from simple assumptions.
- Environmental models allow scientists to study what could happen to organisms in an ecosystem if changes occurred. The models help check predictions without disrupting a large area.
- Pyramids of energy measure the amount of energy available at each trophic level.
- Pyramids of numbers can be drawn by counting the number of organisms at each trophic level in an ecosystem.
- Pyramids of biomass can be drawn by determining the dry mass of organisms.

► Section 2.2 Questions

1. What data would you need to collect to create an ecological pyramid of numbers?
2. What problem might you encounter if you tried to show energy flow through an ecosystem using a pyramid of numbers?
3. How might a pyramid of energy for a grassland community differ between summer and winter? Think about the effects the different abiotic conditions of each season might have on the ecosystem. Use your conclusions to draw a pyramid of energy for each season. Explain any differences between the two pyramids.
4. **Figure 9** shows pyramids of biomass and numbers for a deciduous forest. Explain why the two pyramids are different shapes.
5. Why do energy pyramids have their specific shape?
6. What would be the best source of energy for an omnivore: the plant or animal tissue it feeds on? Explain.
7. A field mouse eats 10 000 g of leaves each year, among other things. If each gram of leaves has absorbed 150 kJ of energy from the Sun, about how much energy is available for the mouse?
8. The producers in a closed ecosystem capture 1.5×10^9 kJ of energy from the Sun each year. The main food chain in the ecosystem has four levels.
 - (a) How much energy is available for the consumers at the top level?
 - (b) Draw a pyramid of energy for the food chain.
9. Despite warnings about future shortages and the pollutants released, we continue to burn oil and coal for energy. What evidence, if any, suggests that attitudes toward conservation are changing? Are they changing quickly enough?

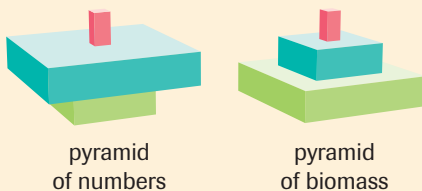


Figure 9

INVESTIGATION 2.1

Constructing Food Webs

Part 1: Antarctic Ecosystem

Research each of the organisms shown in the diagram (Figure 1) and connect them with a food web. Your teacher will provide you with an outline diagram of the organisms. Cut them out and stick them on another piece of paper. Use arrows to connect consumers with their food. Be prepared to explain how the organisms are interrelated.

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Report Checklist

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| <input type="radio"/> Prediction | <input checked="" type="radio"/> Evidence | |

Part 2: Food Webs in Your Community

Using field guides, identify the organisms found in one of the following ecosystems within your community, and construct a food web:

- forested area
- park
- natural grassland
- lake or pond

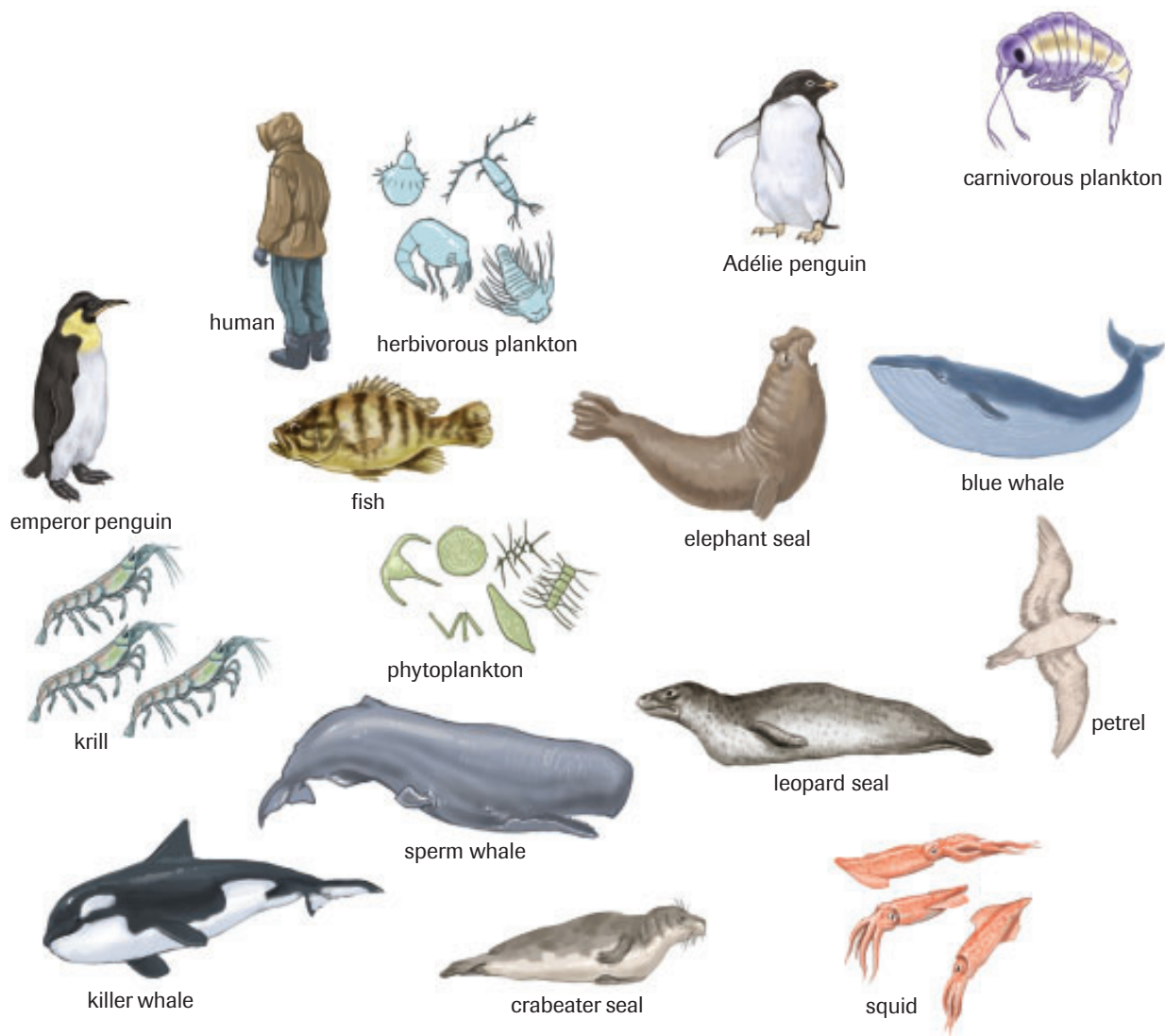


Figure 1

INVESTIGATION 2.1 *continued*

Design

- (a) What area did you choose to study?
- (b) How did you define the area of study?

Procedure

- (c) Provide your procedure.

Evidence

- (d) What organisms did you identify?

Analysis

- (e) Find out more about each organism. How does it fit into the food ecosystem? What does it eat? Which organisms prey on it?
- (f) Construct a food web.

INVESTIGATION 2.2

Light Intensity and Plant Biomass

Through photosynthesis, plants capture solar energy and use it to combine water and carbon dioxide to make glucose. Glucose is then used to fuel its cellular activities and to build other molecules required by the plant. These molecules are used in plant growth, which increases the mass and size of the plant.

Does plant biomass increase with light intensity? Make a prediction. Then, using the materials listed and the design given, write a procedure to address this problem. Make sure you include safety procedures in your design. When your teacher has approved your procedure, carry out the experiment. Ensure you collect the evidence in a clear manner that will allow you to evaluate it later. Your analysis should indicate whether your prediction was correct.

Purpose

To determine how light intensity affects plant biomass

EXTENSION



Constructing Scientifically Valid Procedures

Do you remember how to conduct investigations so that your data are reliable and valid? Listen to this audio clip for a quick review.

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Report Checklist

<input type="radio"/> Purpose	<input type="radio"/> Design	<input checked="" type="radio"/> Analysis
<input checked="" type="radio"/> Problem	<input type="radio"/> Materials	<input checked="" type="radio"/> Evaluation
<input type="radio"/> Hypothesis	<input checked="" type="radio"/> Procedure	<input type="radio"/> Synthesis
<input checked="" type="radio"/> Prediction	<input checked="" type="radio"/> Evidence	

Materials

algae culture
filter paper
light source or access to sunlight
balance (mechanical or electronic)
funnel
two 250 mL beakers
light meter
plastic wrap
retort stand
clamp
graduated cylinder

Design

Plant biomass can be determined by filtering a given quantity from an algae culture and allowing the filter paper and algae to dry.

Outcomes

Knowledge

- explain, in general terms, the one-way flow of energy through the biosphere and how stored biological energy in the biosphere is eventually “lost” as thermal energy (2.1, 2.2)
- explain how biological energy in the biosphere can be perceived as a balance between both photosynthetic and chemosynthetic, and cellular respiratory activities, i.e., energy flow in photosynthetic environments and; energy flow in deep sea vents (chemosynthetic) ecosystems and other extreme environments (2.2)
- explain the structure of ecosystem trophic levels, using models such as food chains and webs (2.1, 2.2)
- explain, quantitatively, energy exchange in ecosystems, using models such as pyramids of energy, biomass, and numbers (2.2)
- explain the interrelationship of energy, matter and ecosystem productivity (biomass production) (2.2)
- explain how the equilibrium between gas exchanges in photosynthesis and cellular respiration influences atmospheric composition (2.2)

STS

- explain that scientific investigation includes analyzing evidence and providing explanations based upon scientific theories and concepts (2.1, 2.2)

Skills

- ask questions about observed relationships and plan investigations (2.1, 2.2)
- conduct investigations and use a broad range of tools and techniques by: performing an experiment to demonstrate solar energy storage by plants (2.2)
- analyze data and apply mathematical and conceptual models by: describing alternative ways of presenting energy flow data for ecosystems: pyramids of energy, biomass, or numbers (2.2)
- work as members of a team and apply the skills and conventions of science (all)

Key Terms

2.1

trophic level	photosynthesis
autotroph	cellular respiration
primary consumer	chemosynthesis
secondary consumer	chemoautotroph
heterotroph	thermodynamics
food web	

2.2

ecological pyramid	monoculture
--------------------	-------------

► **MAKE** a summary

1. Using scientific models, such as a pyramid of energy, draw a diagram that shows the one-way flow of energy through the biosphere. Briefly describe how stored energy in the biosphere is eventually lost as heat.
2. Revisit your answers to the Starting Points questions at the start of the chapter. Would you answer the questions differently now? Why?

► **Go To**

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The following components are available on the Nelson Web site. Follow the links for *Nelson Biology Alberta 20–30*.

- an interactive Self Quiz for Chapter 2
- additional Diploma Exam-style Review Questions
- Illustrated Glossary
- additional IB-related material

There is more information on the Web site wherever you see the Go icon in the chapter.

+ **EXTENSION**



CBC  **radioONE**

QUIRKS & QUARKS

Lovin’ a Lichen

Dr. Irwin Brodo describes lichens—tiny creatures, part algae and part fungus, that are found in all parts of the globe. They are an integral part of the global food web.

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Many of these questions are in the style of the Diploma Exam. You will find guidance for writing Diploma Exams in Appendix A5. Science Directing Words used in Diploma Exams are in bold type. Exam study tips and test-taking suggestions are on the Nelson Web site.

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DO NOT WRITE IN THIS TEXTBOOK.

Part 1

- Bracket fungi, mushrooms, and bread mould can be classified by ecologists as
 - producers
 - herbivores
 - carnivores
 - decomposers
- An example of an ecosystem in equilibrium would be
 - a grassland community in which the number of producers and consumers remains relatively constant over a number of years
 - a naturally occurring grassland community in which fire is prevented
 - a pond ecosystem in which the water temperature changes little throughout the year
 - a pond ecosystem in which the population of algae remains constant throughout the year
- Photosynthesis can best be explained by the following simplified equation.
 - $\text{CO}_2 + \text{H}_2\text{O} + \text{O}_2 \rightarrow \text{energy} + \text{C}_6\text{H}_{12}\text{O}_6$
 - $\text{CO}_2 + \text{H}_2\text{O} + \text{energy} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + \text{O}_2$
 - $\text{energy} + \text{C}_6\text{H}_{12}\text{O}_6 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{O}_2$
 - $\text{C}_6\text{H}_{12}\text{O}_6 + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{energy}$

Part 2

- In your own words, **explain** what is meant by the term *top carnivore*. **Illustrate** your explanation by giving three examples of a top carnivore. **Identify** the ecosystem in which you would find each one.
- Sketch** a food web for a freshwater ecosystem in a dark cave.
- Using the example of a cat and a mouse, **explain** the factors that account for the loss of energy in the transfer from mouse to cat.

Use the following information to answer questions 7 to 9.

Figure 1 shows the flow of energy in an ecosystem.

- Illustrate** the first and second laws of thermodynamics using the components of **Figure 1**.
- Sketch** the predicted shape of an ecological pyramid of numbers using the organisms in **Figure 1**.

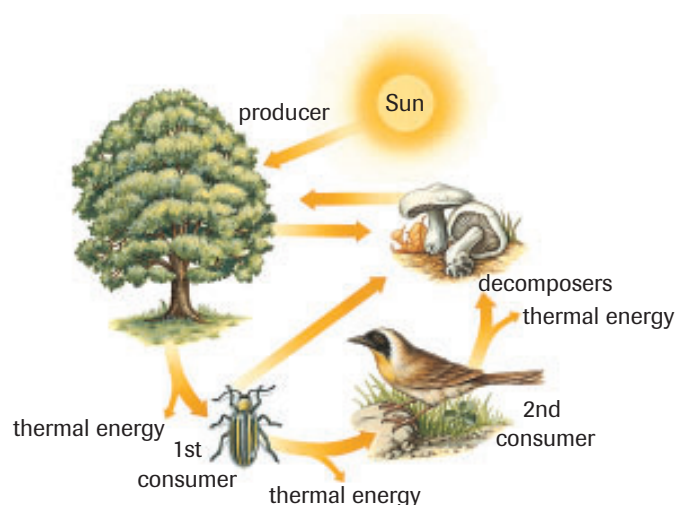


Figure 1

- Sketch** the predicted shape of an ecological pyramid of energy.

- Predict** whether each of the four ecosystems listed in **Table 1** can be sustained. A check mark indicates that the type of organism is present. Write a paragraph to **justify** each answer.

Table 1 Four Ecosystems

System	Autotrophs	Heterotrophs	Decomposers
1	✓		
2		✓	✓
3	✓		✓
4	✓	✓	

- In your own words, **explain** why photosynthesis and cellular respiration are considered to be complementary processes.
- Around the world, habitats available for wild animals have become smaller and smaller as the human population grows. Write a unified response addressing the following aspects of habitat loss.
 - Using an energy flow argument, explain why this shrinkage would affect animals in the highest trophic levels more severely than those in lower levels.
 - Describe** a way to protect wild habitat. How would your solution affect humans?
 - Identify** the type of habitat that might be at the greatest risk of collapse.
- Wolves often prey upon cattle or sheep as well as on natural species, such as deer. Earlier in the century it was considered beneficial to eliminate predators. **Describe** two harmful outcomes of this approach to managing predator populations.
- In underground caves, where there is permanent darkness, a variety of organisms exist. In terms of energy flow, **explain** how this is possible.

15. Based on what you have learned about energy pyramids, **criticize** the practice of cutting down rainforests to grow grain for cattle.
16. **Sketch** complex food webs for a tundra ecosystem and a middle-latitude woodland ecosystem. Conduct additional research to determine the members of the food web, if necessary.
17. By law in Canada, the cutting of forests must be followed by replanting. **Why** do some environmentalists object to monoculture replanting programs?
18. **Illustrate** the two laws of thermodynamics with examples of some common, everyday events.
19. Of the three basic energy pyramids, which best illustrates energy transfer in a food chain? **Explain**.
20. Assuming a 90 % loss of energy across each trophic level, **determine** how much energy would remain at the fourth trophic level if photosynthesis makes available 100 000 kJ of potential energy. **Justify** your answer. **Sketch** a properly labelled pyramid to represent this situation. Could a fifth-level organism be added to the chain? **Explain**.
21. Assume that a ski resort is proposed in a valley near your favourite vacation spot. **Describe** the type of environmental assessment that should be done before the ski resort is built. In providing an answer, pick an actual location you are familiar with and give specific examples of studies that you would like to see carried out.
22. Insect-eating plants such as the sundew are commonly found in bogs across the country. Although referred to as “carnivorous” plants, they are still considered to be members of the first trophic level. Is this the proper trophic level to assign to these plants? Research carnivorous plants, then state the trophic level you think is most appropriate. **Explain** your choice.

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23. Some ecologists have stated that, to maximize the food available for Earth’s exploding human population, we must change our trophic level position. **Describe** the probable reasoning behind this statement. **Predict** any potential biological problems that might occur if this switch were actually made.
24. The sea otter was once an extirpated species in Canada. This species was reintroduced to the west coast from 1969 to 1972. There are now well over a thousand sea otters on the west coast of Canada, but they are still listed as a threatened species. The sea otter eats sea urchins, which

in turn eat algae, such as kelp. When the sea urchin population is kept in control, kelp populations increase. This improves the health of the ecosystem. Higher kelp populations also result in a decrease of barnacles and mussels.

- (a) **Sketch** a food chain that includes the sea otter.
- (b) Sea otters are threatened by oil spills. If the population of sea otters decreases, **predict** what will happen to the population of kelp.
- (c) If the population of sea otters increases, what will happen to the populations of barnacles and mussels?
- (d) Kelp provides shelter for fish. **Predict** how higher populations of kelp might impact fish-eating birds, such as eagles and osprey.
- (e) **Sketch** a concept map showing the impact a decrease in sea otters would have on each species in this ecosystem.

25. The Banff longnose dace, *Rhinichthys cataractae smithi*, now extinct, was found only in Banff National Park, in a marsh into which the Cave and Basin Hot Springs drain. **Summarize** the factors that contributed to the extinction of this species.

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26. **Figure 2** shows a food web.
- (a) Make a chart classifying the species shown into producers, consumers, and trophic levels.
- (b) Use the information in **Figure 2** to **sketch** a pyramid of energy that shows the level of each species. (Since you do not have energy data, just estimate the size of each level.)
- (c) **How** might an increase in the population of snowshoe hares affect the owl over a short period of time? over a long period of time? **Explain** your reasons.
- (d) **Predict** what would happen to the population of owls if hawks were introduced to the ecosystem.

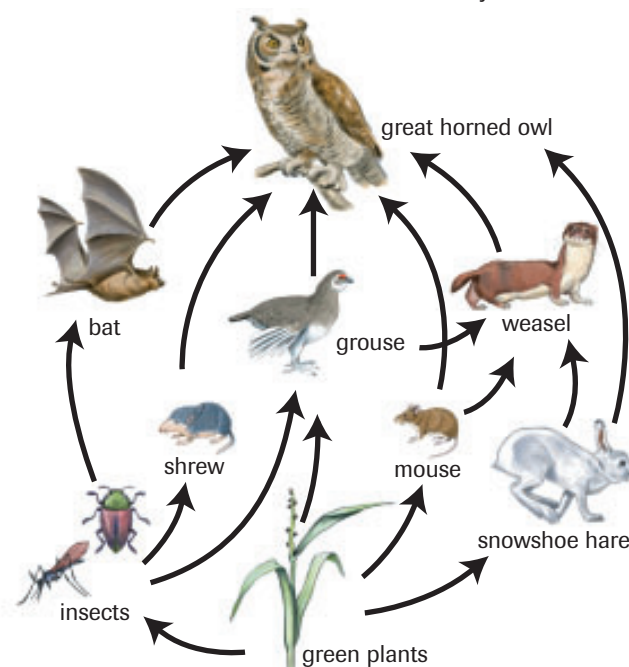


Figure 2